TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 588

THE BEHM ACOUSTIC SOUNDER FOR AIRPLANES
WITH REFERENCE TO ITS ACCURACY

By Ernest Schreiber

Jahrbuch 1930
der Deutschen Versuchsanstalt für Luftfahrt

Washington
October, 1930

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THE BEHM ACOUSTIC SOUNDER FOR AIRPLANES WITH REFERENCE TO ITS ACCURACY.*

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Relative altimetry is of great importance for increasing the safety in aerial transportation, because it makes possible safe flying at night, by poor visibility, and notably, when landing. Among the instruments of this type is the Behm sounder, which operates on an acoustic principle.**

Principles of Acoustic Altimetry

Acoustic altimetry is based upon the measurement of the time interval required for the sound to travel from the aircraft to the ground and back to the aircraft as an echo. From this interval it is possible to arrive at the height at which the airplane flies. With c as the velocity of sound in the free atmosphere and Δt as the total elapsed interval of the sound, the sound path covered is $s_o = c\ \Delta t$, and the corresponding height is $h_o = \frac{1}{2}\ c\ \Delta t$, the velocity of sound being measured in meters per second; and Δt in seconds. According to the ex-

*"Das Behmlot für Flugzeuge und die mit ihm erzielte Genauigkeit." Jahrbuch 1930 der Deutschen Versuchsanstalt für Luftfahrt, pp. 483-490.

**Behm-Luftlot, Zeitschrift für Flugtechnik und Motorluftschiffahrt, Vol. 15, 1924, p. 265; and A. Behm, "Das Behmlot und seine Entwicklung als akustischer Höhenmesser für Luftfahrzeuge." Berichte und Abhandlungen der Wissenschaftlichen Gesellschaft für Luftfahrt, No. 13, 1926, p. 56.

periments of R. Ladenburg and E. v. Angerer,* the velocity of sound is computed from the formula $c = 330.7 + 0.66\ T$ m/s, T being the temperature in centigrade. The effect of meteorological conditions, such as temperature, humidity, or barometric pressure can be practically ignored. The sound velocity is more affected by temperature changes than by humidity or barometric pressure.

The extent of the temperature effect is calculated as follows. According to our first formula, we have

$$h_o = \frac{1}{2}\,\Delta t\ c = \frac{1}{2}\,\Delta t\,(a + b\,T)$$

where $a = 330.7$ and $b = 0.66$. Differentiating h_o we have

$$\frac{d\,h_o}{d\,T} = \frac{1}{2}\,b\,\Delta t$$

and

$$\frac{d\,h_o}{h_o} = \frac{b}{a + b\,T}\,d\,T$$

A temperature increase of $dT = 1^\circ C$ produces in $d\,h_o$ a $\frac{66}{340.6} = 0.19\%$ change, assuming $T = 15^\circ C$ when calibrating the instrument. Accordingly, a 5° change in temperature produces about a 1% change in h. So it will be seen that the temperature effect may be safely ignored.

Owing to the air speed v of the airplane, equation

$$h_o = \frac{1}{2}\,c\,\Delta t$$

*R. Ladenburg and E. v. Angerer, "Über die Ausbreitung des Schalles in der freien Atmosphäre. Bericht über die Versuche des Kommandos der Artillerie-Prüfungskommission in Flandern. Berlin, Reichsdruckerei 1918.

must be corrected, which, according to Figure 1, is quite simple. The true altitude is

$$h = \frac{\Delta t}{2} \sqrt{c^2 - v^2}.$$

If v_0 is the speed of the airplane upon which the design of the altitude scale of the sounder is based, the indicated altitude for a certain Δt becomes

$$h = \frac{1}{2} \Delta t \sqrt{c^2 - v_0{}^2},$$

while it should be

$$h_{soll} = \frac{1}{2} \Delta t \sqrt{c^2 - v^2}.$$

Now we have

$$\frac{h}{h_{soll}} = \frac{\sqrt{c^2 - v_0{}^2}}{\sqrt{c^2 - v^2}}$$

so that

$$h - h_{soll} = \frac{h_{soll} \left(\sqrt{c^2 - v_0{}^2} - \sqrt{c^2 - v^2}\right)}{\sqrt{c^2 - v^2}}.$$

The difference of $h - h_{soll}$ yields the error f, for which the altitude, indicated on the sounder, must be corrected. Figure 2 is a graph which shows these speed errors from 20 to 60 m/s, and for the h_{soll} values up to 100 m. This graph likewise shows that the air speed may be ignored when using the sounder. Its effect can still further be reduced by calibrating for a slightly higher speed (v_0 = 20 m/s).

Lastly, we examine the effect of the distance a of both microphones on the height measurement.

Taking into account the calibrated air speed v of the airplane, the distance a_0 of the points of measurement, and that during the installation, the impulse microphone AM in the flight direction is in front of the echo microphone EM during the calibration (Fig. 3I); the equation for altitude h indicated by the Behm sounder is:

$$\text{I.} \qquad h^2 = \frac{1}{4} c^2 \Delta t^2 - \frac{1}{4} (a_0 - v_0 \Delta t)^2 =$$

$$\frac{1}{4} \Delta t^2 (c^2 - v_0^2) + \frac{1}{2} a_0 v_0 \Delta t - \frac{1}{4} a_0^2 .$$

For an arbitrary distance a of the microphones and for an arbitrary air speed v the value of h should be

$$\text{II.} \qquad h_{soll}^2 = \frac{1}{4} \Delta t^2 (c^2 - v^2) \pm \frac{1}{2} a v \Delta t - \frac{1}{4} a^2 ,$$

the upper or lower prefix being valid, according to whether the impulse microphone AM is installed in front of or behind the echo microphone EM (Figs. 3I and 3II).

From these two equations (I and II) the relations between h and h_{soll} are as follows:

$$h^2 = - \frac{a_0^2}{4} + \frac{c^2 - v_0^2}{c^2 - v^2} \left(\frac{a^2 + 4h^2_{soll}}{4} + \frac{a^2 v^2}{2 (c^2 - v^2)} \right) +$$

$$+ \left(\frac{a_0 v_0}{2} \mp \frac{c^2 - v_0^2}{c^2 - v^2} \frac{a v}{2} \right) \sqrt{\frac{a^2 + 4 h^2_{soll}}{c^2 - v^2} + \left(\frac{a v}{c^2 - v^2} \right)^2} \mp$$

$$\mp \frac{a_0 v_0}{2} \frac{a v}{c^2 - v^2} ,$$

and the correction $f = h - h_{soll}$ between the recorded indications and the corrected height values is

$$h - h_{soll} = \sqrt{-\frac{a_o^2}{4} + \frac{c^2 - v_o^2}{c^2 - v^2}\left(\frac{a^2 + 4h^2_{soll}}{4} + \frac{a^2\ v^2}{2(c^2 - v^2)}\right) + \left(\frac{a_o\ v_o}{2} \mp \frac{c^2 - v_o^2}{c^2 - v^2}\ \frac{av}{2}\right)\sqrt{\frac{a^2 + 4h^2_{soll}}{c^2 - v^2} + \left(\frac{av}{c^2 - v^2}\right)^2}} \mp \frac{a_o\ v_o}{2}\ \frac{av}{c^2 - v^2} - h_{soll}$$

In Figures 4 A, B, C, we show the effect of distance a on the height measurement graphically, assuming $v = 20$ m/s, 40 m/s, and 60 m/s. The differences f are plotted as ordinates, and the figures 0 to 80 m, assumed as the microphone distance a, as abscissas. The calculation was based on $a_o = 2.6$ m, $v_o = 20$ m/s, and $c = 340.6$ m/s.

The legend of Figure 4 states that the curves to the right (or left) of the ordinate axis are for the case where the impulse microphone AM in the flight direction is installed ahead of (or behind) the echo microphone. The microphone distances a up to 10 m, mostly applying to aircraft, are shown at an enlarged scale in Figures 5 A', B', C'. They prove that the distance a up to 5 m has practically no appreciable effect on the acoustic sounding.

The Behm Sounder for Airplanes

The Behm acoustic sounding device consists of

a) the time-interval recorder for measuring Δt,

b) the impulse and the echo microphones,

c) the detonating mechanism for producing the sound.

The time interval recorder comprises the timing disk, the sonometer, the light source, the altitude scale and switch box.

A diagrammatic view is shown in Figure 6. Z is a rotating disk with a second smaller disk. The latter has a toothed armature which meshes with the toothed end of a lever H. In the pivot of this lever a mirror is mounted which deflects the image of the filament of lamp L, reflected by lens O, so that it becomes visible on the altitude scale HS. Lever H further carries an impulse spring which always pulls armature A_n at the rim of the recorder disk near electromagnet M_z, when inoperative. The recorder disk, in addition, carries two stops, spaced in such a manner that stop A_1 is held against a leaf spring Bl_1, when the recorder disk is at rest, and at the same time stop A_2 strikes a second leaf spring Bl_2 close to spring Bl_1, as soon as the image of the lamp reaches the upper edge of the altitude scale. This spring then breaks the motion of the disk and brings it as well as the mirror, into the original position.

When an electric current passes through impulse microphone

AM to electromagnet M_z, there is a magnetic pull on the armature A_n of recorder disk Z and leaf spring Bl_1 is put in tension by stop A_1. At the moment of dispatching the cartridge, the current in microphone AM changes and the magnetic pull of electromagnet M_z is reduced so that the pressure of leaf spring Bl_1 sets the recorder disk in motion.

The sonometer S consists of an electromagnet M_s, with a leaf spring in front of its pole shoe. This carries on its upper end a glass lens P of very short focal distance, and a filament lamp in front of it. This lens in connection with O and the mirrors on recorder disk Z, throws the image of the filament on scale HS. When the current runs through electromagnet MS and echo microphone EM, the leaf spring assumes a position corresponding to the magnetic pull of the pole shoe. The glowing filament of lamp L appears as an illuminated point at zero position of the scale. When the sound wave arrives at the microphone EM, it causes a change in the electrical resistance of EM and through it in the setting of lens P; and the light point shifts laterally on the scale.

During sounding the rotation of the recorder disk produces wandering of the illuminated point along the scale. At the moment of arrival of the echo this point is laterally deflected and thus determines the point of the scale where the reading is to be made. This reading gives the altitudes directly, because the scale is graduated in meters, not in parts of a second.

The new Behm sounder for airplanes carries improvements in sonometer, altitude scale, switch box and microphones, which were not incorporated in those just described, and which we shall mention here.

Suitable arrangement of the leaf spring increased the damping in the sonometer considerably, with the result that the light point during sounding remains practically unaffected by the airplane vibrations, if correctly installed. As a result, the beginning of the echo can be distinctly heard, as well as any successive echos caused by the surroundings.

The altitude scale range has been raised from 20 to 50 meters. In addition, the light point, when at rest, remains within a shaded portion of the scale. As a result of this arrangement the vibrations of the sonometer, released by the direct sound waves along the airplane at the moment of firing, remain within the shaded portion of the scale and escape the eye of the observer. This facilitates the reading of small altitudes.

In the new instrument, the switch box (Fig. 7) is separate from the time-interval recorder, and is connected by cable with the tapping or branching ends. The front shows the two resistors W_1 and W_2 for regulating the current charge of the microphones, and the sensitivity of the recorder disk, as well as the lateral adjustment of the light point on the altitude scale. Below is the main switch H_1 and below it a small switch H_2, which is moved to the left when the recorder disk is to be returned to zero. Switching H_2 to the right, the light indicator remains visible even while the disk returns to zero. This latter arrangement was found suitable when making soundings at more than 1000 m (3280 ft.), but in that case the altitude scale must be specially calibrated.

The receiving instruments, the impulse and the echo microphones are housed in a tight metal casing M (Fig. 8), with tube R for connecting with the outside air. The microphones are elastically suspended in aluminum rings A. The incoming echo is amplified in T, screwed to tube of the echo microphone.

The detonating or firing mechanism is installed outside on the port or starboard side, as conditions demand (Fig. 9). Next to it is the impulse microphone, either attached to the firing mechanism and bolted to the side of the fuselage or separate from it. The echo microphone EM is behind the sound source, at about 2 meters from the impulse microphone, and fastened to the floor of the airplane, and at a place as safe from vibrations as possible (Fig. 10). It is absolutely essential to make the installation of the echo microphone and of indicator A as safe from any disturbance as possible. We accomplished this in our tests by bedding the echo microphone in a box lined with sponge rubber, the box being suspended from rubber cords. The amplifier in the bottom of the airplane was connected by a 10 centimeter long soft rubber tubing to the microphone attachment to prevent the mechanical vibrations of the amplifier from reaching the microphone. The amplifier was placed in a wooden box H lined with cotton wool. The indicator A was suspended from rubber cords to protect the time-interval recorder against airplane vibrations. These protective measures proved themselves to be very satisfactory.

Testing of Behm Sounder - Accuracy of Recording

The accuracy of the time-interval record was tested by investigating its dependence on the impulse interval Δt, and the effect of different temperatures. The various Δt values were established by a contact pendulum, whose pendulum bob, when falling from a constant height, successively releases two contacts. These contacts form, in place of the microphones, the connection between the electromagnet of the recorder disk, the sonometer, and one battery each, respectively. The impulse periods Δt were obtained by changing the contact spacing, the first contact being kept stationary while the second was shifted to certain marks. To determine the time intervals corresponding to the different settings, we connected each contact to a measuring coil of an oscillograph which, when the pendulum dropped, recorded the interruption of the current. A 50 amplitude tuning fork was used to plot the respective time curve. The impulse period Δt is given by the number of tuning fork vibrations between the deflections which are visible on the oscillogram. The time intervals (Δt values) corresponding to the different contact settings are shown in Table I, by an assumed sound velocity of $c = 340$ m/s.

From this table we prepared the comparative values for the altitude scale, by dividing the sound path by 2, taking into account the microphone spacing in the airplane as well as their mean distance from the ground for zero flight altitude.

TABLE I. Determination of Differences in Interval Corresponding to the Different Contact Settings

Contact setting	Time interval s	Path of sound m
1	0.046	15.7
2	0.072	24.6
3	0.091	31.0
4	0.122	41.6
5	0.160	54.5
6	0.191	64.8
7	0.250	85.0

TABLE II. Comparative Values for Altitude Scale

Contact setting	Calculated altitude m	Indicated altitude (longer range) m	Δh	Indicated altitude (shorter range) m	Δh
1	5.9	5.0	-0.9	5.4	-0.5
2	10.4	10.0	-0.4	10.6	+0.2
3	13.7	14.5	+0.8	14.0	+0.3
4	18.9	19.5	+0.6	19.5	+0.6
5	25.4	25.0	-0.4	25.3	-0.1
6	30.2	30.0	-0.2	30.8	+0.6
7	40.7	40.0	-0.7	41.0	+0.3

The long range was tested up to 40 m only, due to the inability of the pendulum to measure time differences beyond 1/4 second. The indicated figures differ from the computed figures in both ranges, but they are of no significance so long as they are not exceeded very much within the practical range of use.

In the above measurements the magnetizing current of the electromagnet of the recorder disk and the sonometer were completely interrupted during the dropping of the pendulum, leaving the time-interval recorder subsequently dead. But, since in practical sounding the current retains its voltage after measuring, it became necessary to simulate the actual conditions. So we plugged in a transformer each in the original circuit, one winding, having the same ohmic resistance as the microphone, to the electromagnet of the recorder disk, and to the sonometer, respectively, and to one battery each. The high ohmic coil of each transformer was attached to the corresponding pendulum contacts. The current impulse induced by opening the contacts in the low ohmic coils changes the quiescent current in the time-interval recorder and releases the indicator. In a second test we used two noninductive resistors in place of the transformers, which, upon opening the contacts, weakened the current so that the time-interval recorder was able to run. The results of both these tests agree very closely with the above data.

That the correct method of operation of the Behm sounder depends to a great extent on the intensity of the current flowing through the sonometer, is proved by the following experiment. We connected two transformers in both circuits of the time-interval recorder to take the place of the microphones, and regulated the voltage of the circuit formed by the contact pendulum so that the induced current in the sonometer, upon opening the contacts, released a still clearly definable deflection, but the altitude scale showed:

Normal current impulse (Sonometer deflection about 10-15 mm)	Current impulse weakened (Sonometer deflection about $\frac{1}{2}$-1 mm)
15.5 m	25.3 m
13.1 "	17.0 "

Thus it will be seen that the errors in altitude indication are quite pronounced when the current passing through the sonometer produces only a slight deflection of the glass lens.

In several instruments we determined the accuracy of measurement by echo, with an airplane hangar as reflecting area. The impulse and echo microphones and the firing mechanism were set up at a given distance from the hangar. The echo microphone was placed in a soft, rubber-lined wooden box and set in a tent facing the hangar. The results are shown in Table III.

TABLE III. Accuracy Test by Echo

Actual distance A_0 (m)	Measured distance A (m)	ΔA m
Long range of Behm Sounder L_3 No. 008		
12.0	11.2	-0.8
27.6	27.1	+0.5
38.2	38.6	+0.4
50.0	51.9	+1.9
60.0	62.8	+2.8
70.0	72.7	+2.7
80.0	81.6	+1.6
Short range of Behm Sounder L_3 No. 008		
11.8	10.8	-1.0
19.5	19.0	-0.5
27.7	27.2	-0.5
38.0	38.3	+0.3

The discrepancies in ΔA are slight enough to be negligible in practical altimetry.

Knowledge of the effect of cold on time-interval recorder indications is of particular importance. We tested this effect by placing the instrument in the refrigerator of the D.V.L. at different temperatures, and noting every 5° change through an observer's window. Beyond -20°C the measurements failed, because the scale became covered with a thick layer of frost. The effect of the cold on the indications is shown in Figure 11, - about 6° for the long range, and from about -4° downward for the short range. One remarkable feature was that the Δh values by a given temperature were unaffected by the actual heights (0 - 40 m). The defined Δh are so small within the short range that the temperature effect may be ignored. In the long range test the discrepancies for Δh were greater, 1 m and more for -10°, and 2.3 m for -20° temperature.

Flight Tests

These were made with the Dornier Merkur D 969, the instrument, type L_3 No. 014, installed as stated on page 6. The indicator with switch box was suspended on the starboard side, with the echo microphone close to it. On the outside we bolted the detonating mechanism or firing head to a strong, large board, to prevent the powder dust from damaging the airplane. The impulse microphone was on the inside of the port side and connected with the board carrying the detonator.

Prior to each sounding we regulated the current for the recorder disk so that the zero position of the disk was undisturbed by the airplane vibrations. The zero of the light indicator was set in approximately the center between the scales by regulating the voltage. The desired altitude was read on the long-range scale.

These tests were made in very squally weather in the presence of an official of the Behm Sounder Company. First, we fired a shot each at approximately 90, 80, 60, 40 m, and measured the corresponding height with the sounder. The engine was throttled (1200-1250 r.p.m.). At the same time the position of the airplane was determined from the ground by a mapping camera. Then we sounded the small heights by gliding with idling engine, firing about three shots in 3 to 5 seconds' succession, while the camera snapped the airplane three times on the same plate (Fig. 12). The recorded heights then were compared with those determined by the camera.

The observer on the ground operates the instantaneous shutter of the camera as soon as he sees the puff of smoke. By flying from 90 to 40 m altitude with a statoscope, possible errors in timing the shutter release to the smoke release were reduced. When gliding, the airplane was so close to the observer that he could always see the smoke very plainly.

For comparing the indicated altitudes with those measured by the camera, corrections must be made, which are caused by the temperature and by the installation method. The calibration scale is based on 15°C, a 2.60-meter distance of the microphones and a 1.80-meter mean distance of these instruments from the ground for zero flight altitude. During the test flight the air temperature was 20°, the basis 2 m, and the mean distance from the ground 1.67 m. Although the last two quantities have practically no effect, that of the temperature on the velocity of sound must be corrected.

The heights determined by the camera may be considered as true heights of the airplane because the mean error does not exceed 30 to 40 cm. The height difference is shown in column five, Table IV, showing a mean error of ±3.5 m (11.4 ft.) for the acoustic method in adverse weather conditions. For heights above

19 m, this error is practically of no import. During these tests we also made many acoustic measurements at less than 10 m, but which were not included in our table, because the camera could not record these due to unfavorable position of the airplane. Hence, further flight tests are needed to decide the accuracy of the Behm acoustic sounder at low altitudes.

TABLE IV. Flight Test Data

Time	Behm soundings h_a m	h_a corrected m	Measurement by camera h_{ph} m	Difference Δ m	$\Delta\cdot\Delta$
(1)	(2)	(3)	(4)	(5)	(6)
July 5, 1929					
hr. min. sec.					
10 22 7	85	85.8	83.0	−2.8	7.84
25 53	45	45.5	49.1	+3.6	12.96
28 59	55	55.6	58.8	+3.2	10.24
33 36	60	60.6	53.5	−7.1	50.41
Aug. 5, 1929					
hr. min. sec.					
9 15 50	100	101	101.9	+0.9	0.81
18 33	65	65.6	70.5	+4.9	24.01
21 7	60	60.6	61.4	+0.8	0.64
23 35	80	80.8	84.0	+3.2	10.24
26 8	85	85.8	81.2	−4.6	21.16
36 34	30	30.3	30.7	+0.4	0.16
36	25	25.2	24.5	−0.7	0.49
54	20	20.2	19.7	−0.5	0.25
43 7	42	42.4	42.9	+0.5	0.25
10	30	30.3	33.9	+3.6	12.96
13	25	25.3	23.9	−1.4	1.96
46 13	35	35.4	38.1	+2.7	7.29
14	28	28.3	28.3	±0.0	0.00
18	23	23.2	19.3	−3.9	15.21
49 32	40	40.4	43.7	+3.3	10.89
36	30	30.3	24.8	−5.5	30.25
55 16	65	65.7	59.8	−5.9	34.81

$[\Delta\cdot\Delta] = 253$

$n = 21$

Sum of positive $\Delta = 27.1$

" " negative $\Delta = 32.4$

one $\Delta = 0$

$$\text{Mean error} = \pm \sqrt{\frac{[\Delta \cdot \Delta]}{n}} = \pm \sqrt{\frac{253}{21}} = \pm\ 3.5\ \text{m.}$$

Future Development of Instrument

One disadvantage in handling the firing mechanism is the necessity of operating the firing head and at the same time try to read the indications correctly. However, an automatic firing device has already been developed by the C. G. Haenel arms factory, and its method of operation as well as the results obtained with it will be published upon completion of the tests which are now being made.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

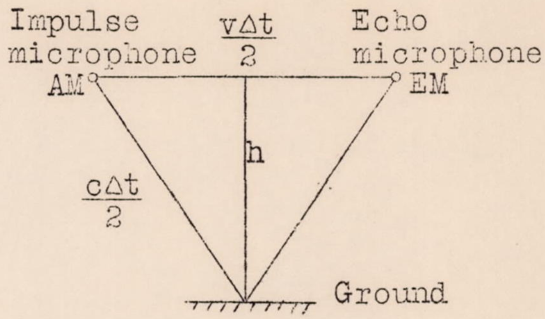


Fig.1 Propagation of sound with respect to airplane speed, v.

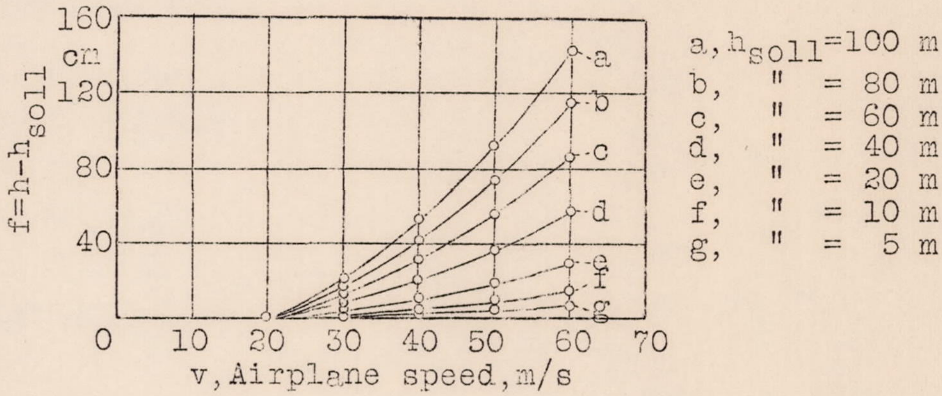


Fig.2 Effect of sounding error f, from air speed v.

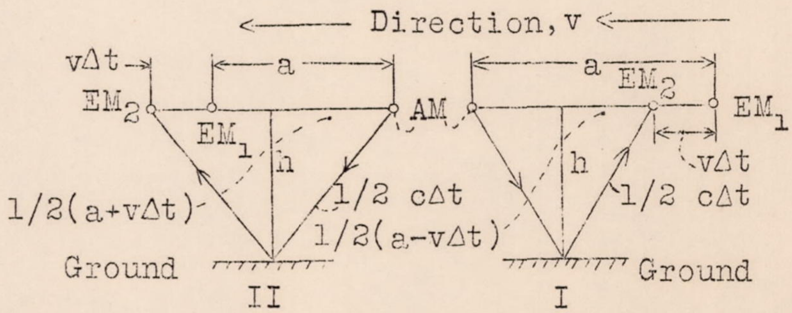
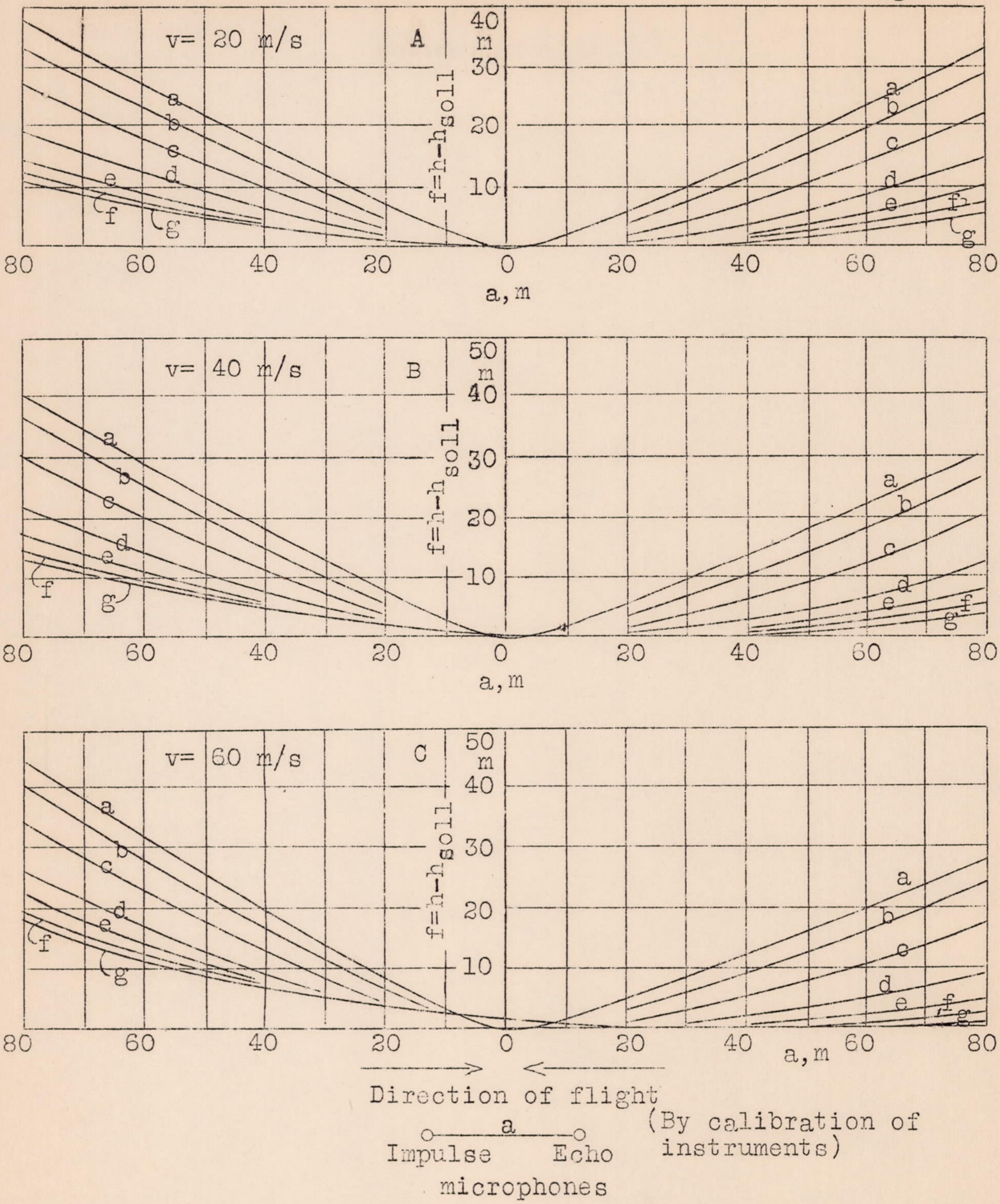
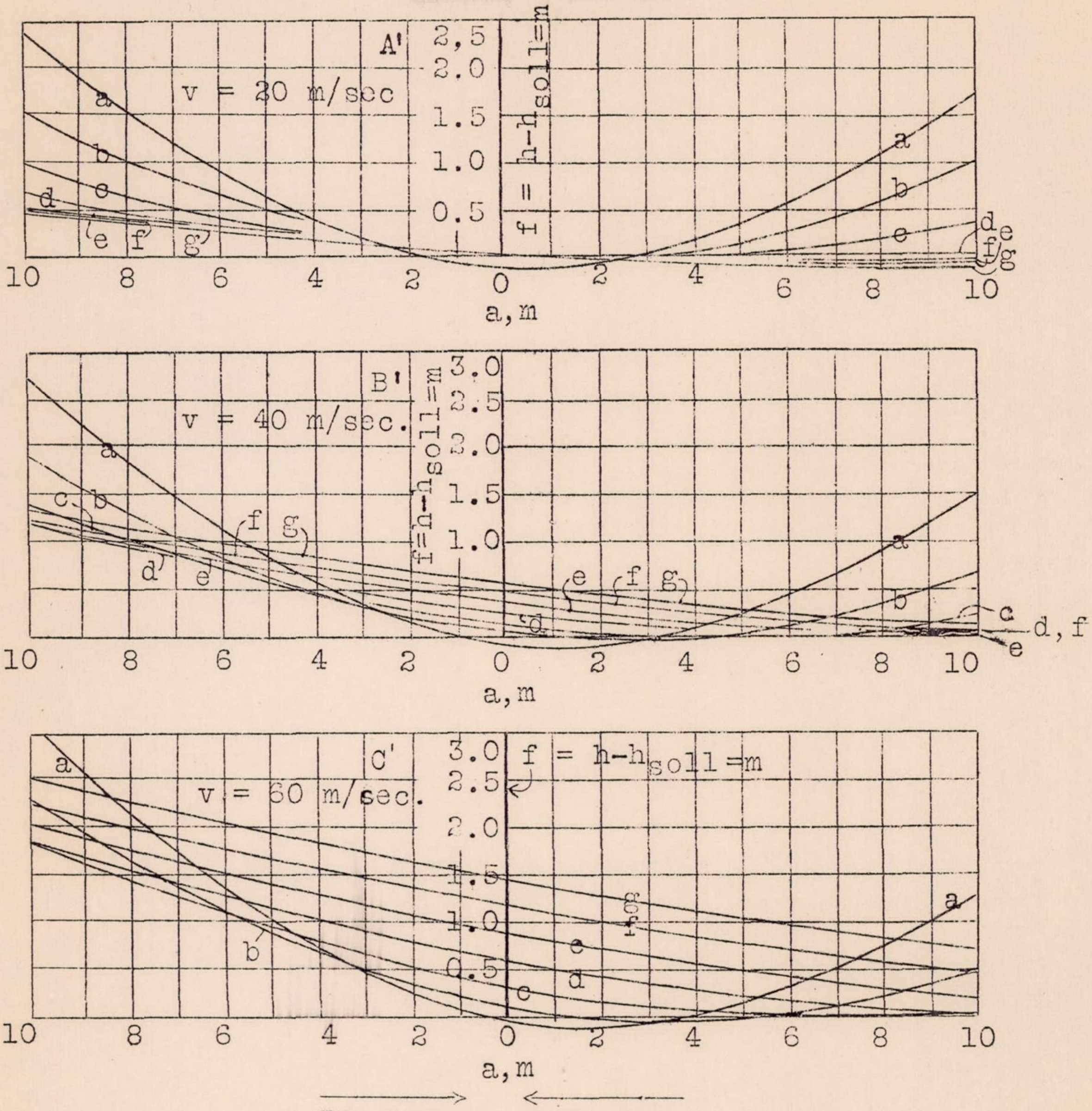


Fig.3 Propagation of sound with respect to distance a, of impulse and echo microphone.



a, h_{soll} = 5 m
b, " =10 m
c, " =20 m
d, h_{soll} =40 m
e, " =60 m
f, " =80 m
g, h_{soll} =100 m

Fig.4 Sounding error with respect to airplane speed v, and distance a of impulse and echo microphone, represented for v=20 m/sec., 40 m/sec. and 60 m/sec.



Direction of flight

Impulse a Echo microphones (By calibration of instruments)

a, h_{soll} = 5 m
b, " =10 m
c, " =20 m
d, h_{soll}=40 m
e, " =60 m
f, " =80 m
g, h_{soll}=100 m

Fig.5 Enlargement of Fig.4 for microphone distances up to 10 m.

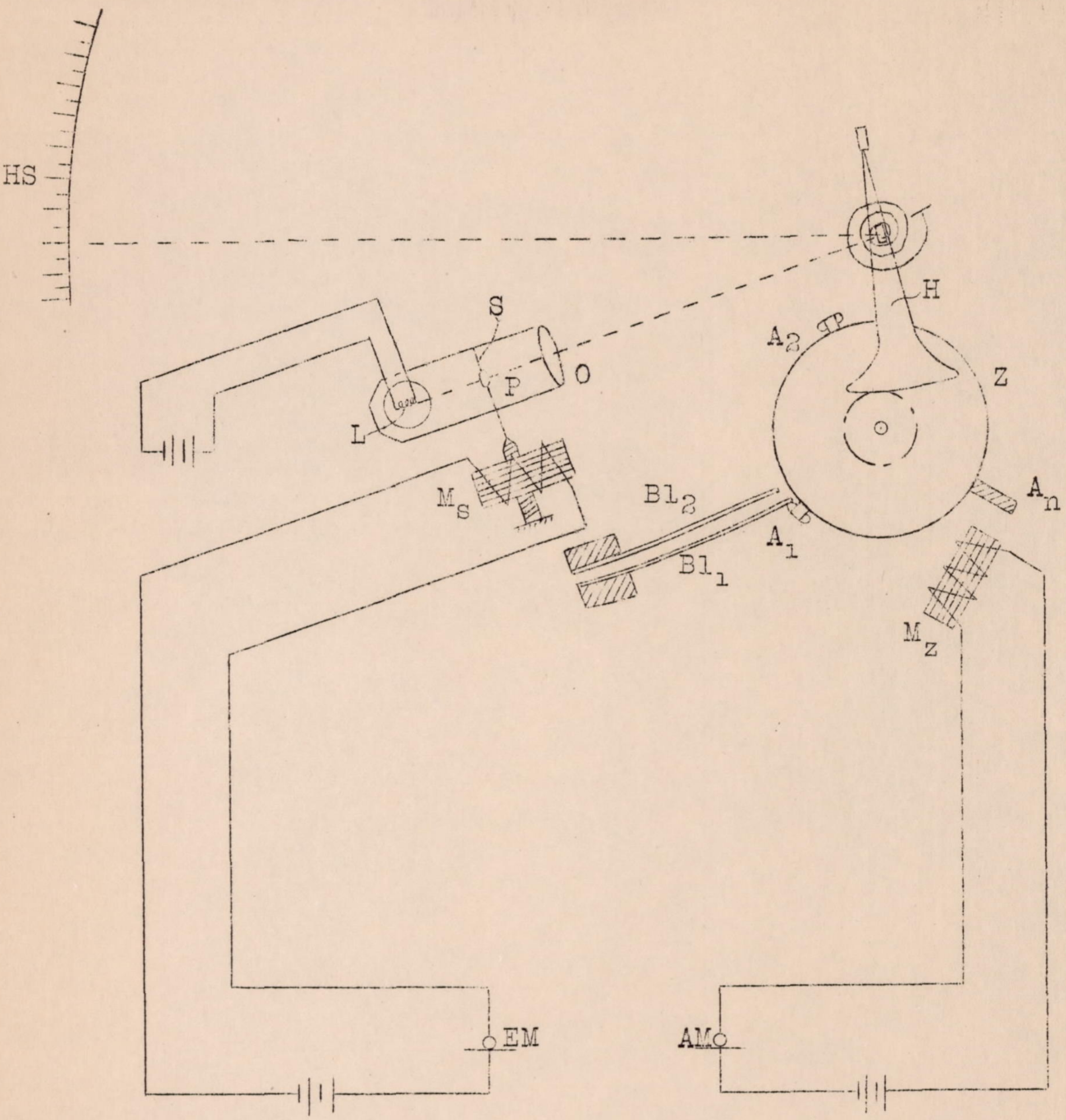


Fig.6 Diagram of interval recorder.

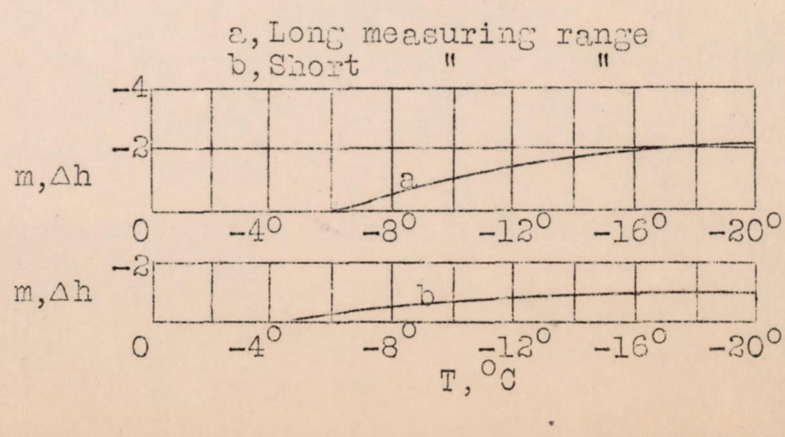


Fig.11 Effect of temperature on the Δh values.

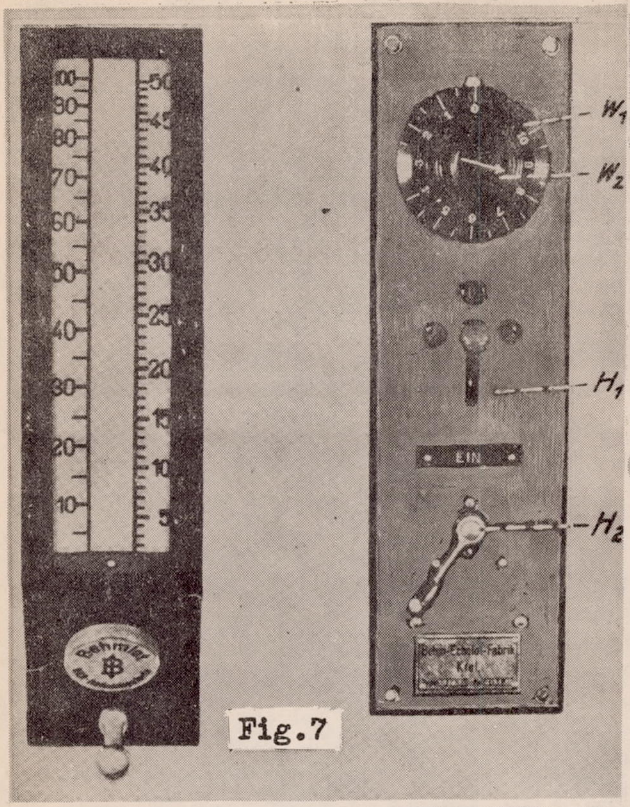


Fig.7

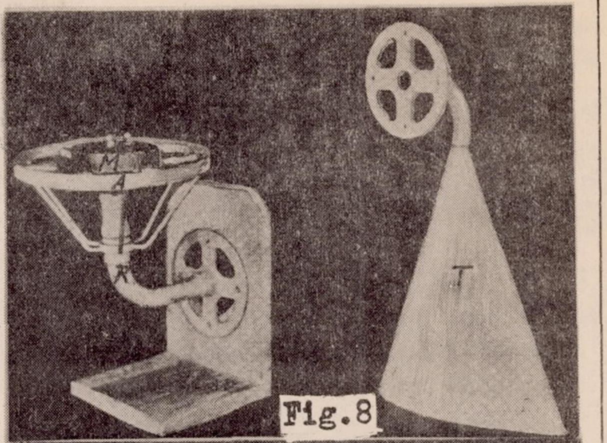


Fig.8

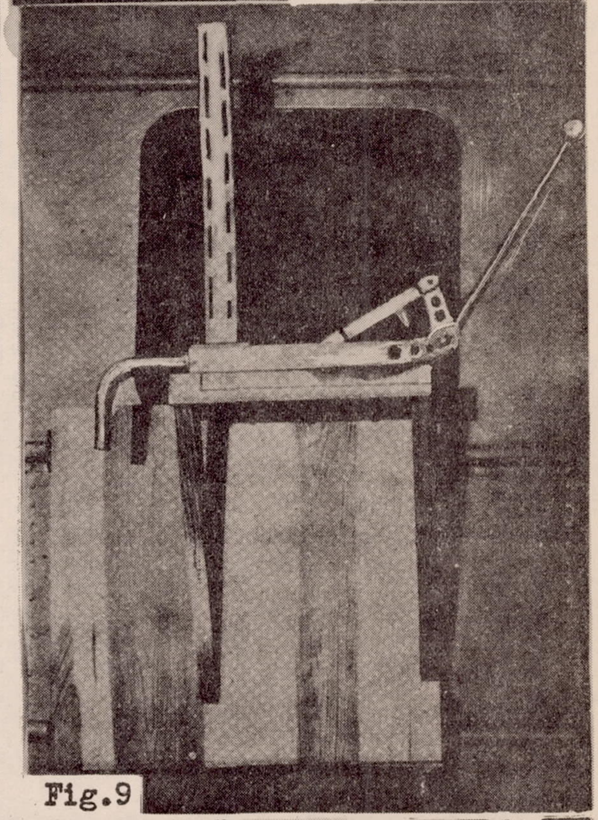


Fig.9

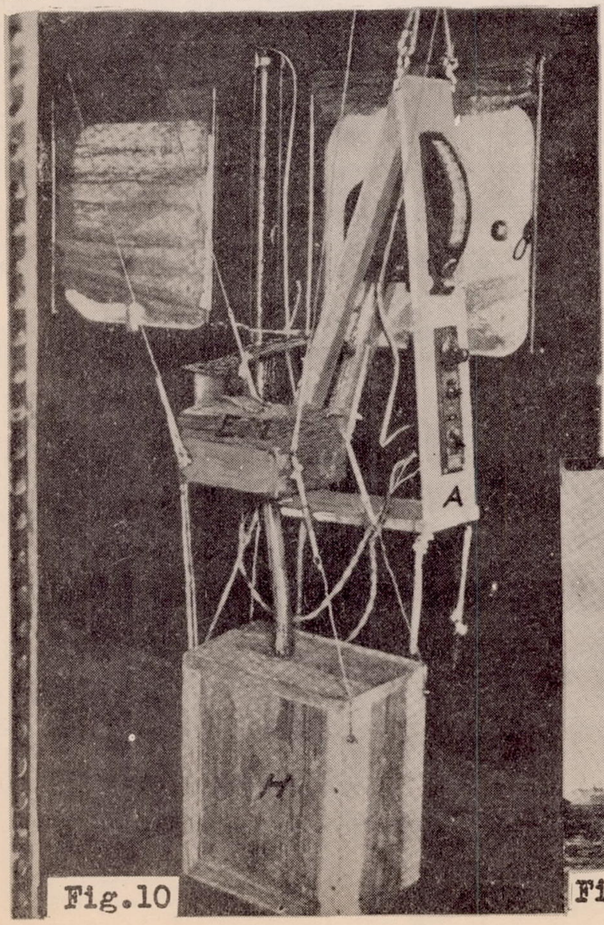


Fig.10

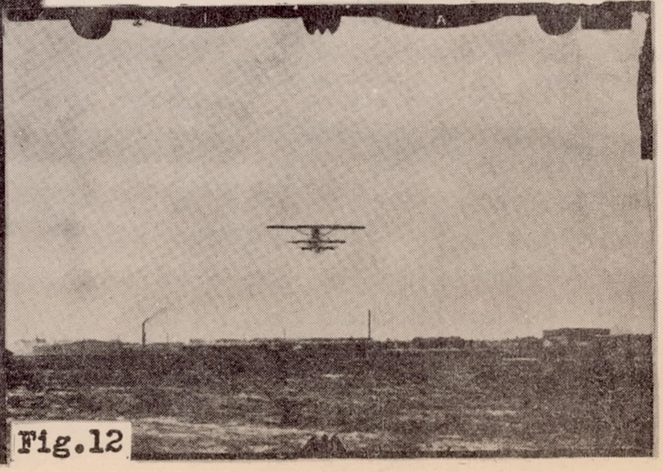


Fig.12